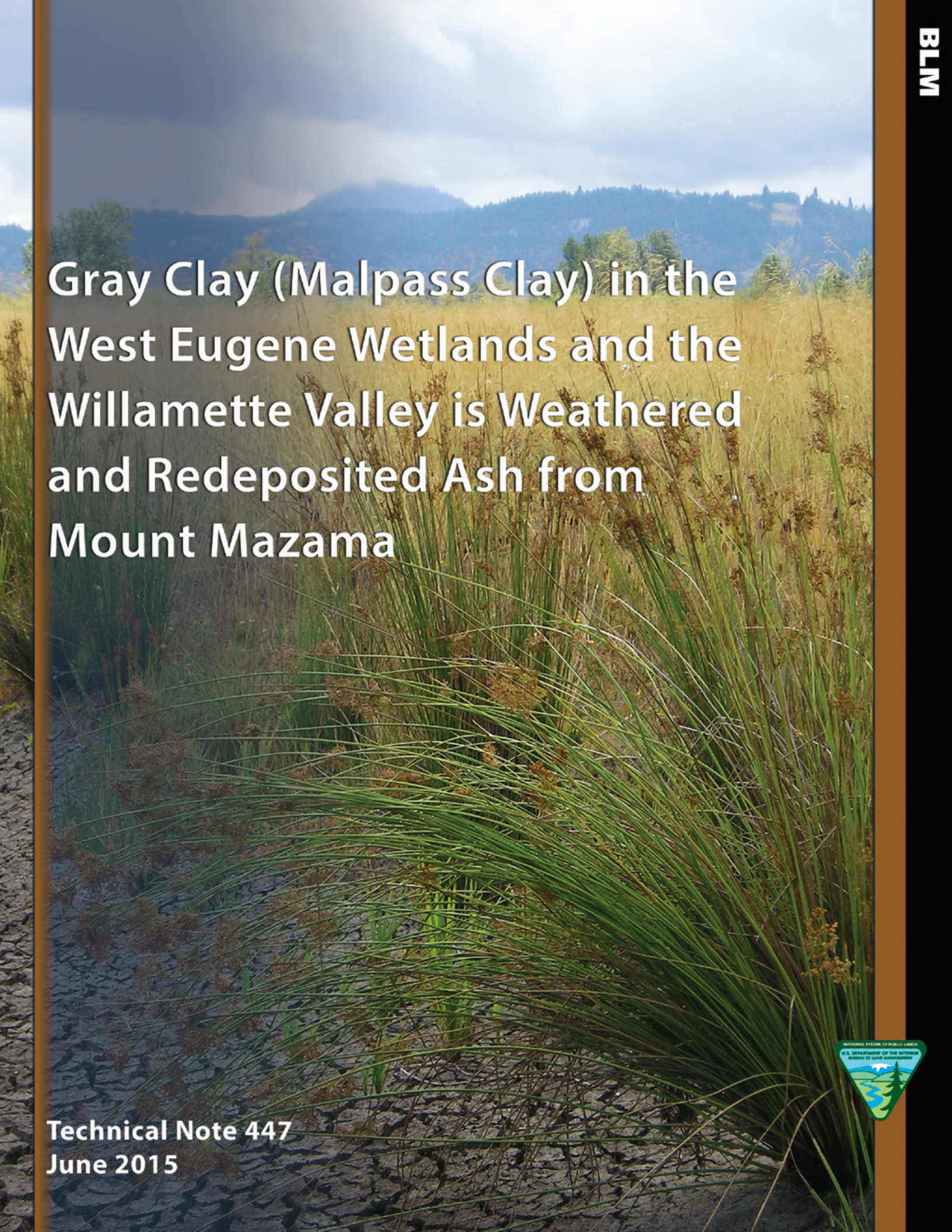

Gray Clay (Malpass Clay) in the West Eugene Wetlands and the Willamette Valley is Weathered and Redeposited Ash from Mount Mazama

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Gray Clay (Malpass Clay) in the West Eugene Wetlands and the Willamette Valley is Weathered and Redeposited Ash from Mount Mazama

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JUNE 2015

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Abstract

The climactic eruption of Mount Mazama approximately 7,600 years ago distributed airfall tuff throughout what is now eastern and offshore Oregon. This distinctive tephrostratigraphic marker had been thought to be absent across the Willamette Valley. X-ray diffraction, examination of pyrogenic mineral suites, and new high-resolution radiometric dating ($^{40}AR/^{39}AR$) of Malpass clay from tuffaceous marker beds suggest that it is the missing ash from Mount Mazama. Over time and weathering, the ash has transformed into a smectitic gray imogolite and clay. Analysis of this widespread gray clay provided a radiocarbon date of 6,850 ± 70 years before present. Radiometric dating of the clay provided the ages of 7,987 ± 102, 8,451 ± 57, and 8,540 ± 48 years before present. These dates are comparable with that of the climactic eruption of Mount Mazama.

Introduction

Malpass clay is a widespread gray clay originating from the Holocene and found today in the Willamette Valley in Oregon (Figure 1). Theories of its origin vary from the idea that the clay came from weathering in place (Nikiforoff and Drosdoff 1943), from erosion from the Coast Range mountains (Parsons and Balster 1965, 1966; Balster and Parsons 1968, 1969), from deposition of the Missoula floods roughly 12,500 years ago (Gelderman and Parsons 1972; Roberts 1984), or from a separate windblown deposit (Glasmann et al. 1980; O'Connor et al. 2001). This technical note presents evidence that the unusual composition of Malpass clay and a suite of rhyodacitic minerals in other soils and sediments are derived from Mount Mazama volcanic ash, which has weathered in place and redeposited from surrounding hillslopes (Norgren 1962; Glenn 1965; James and Baitis 2003).

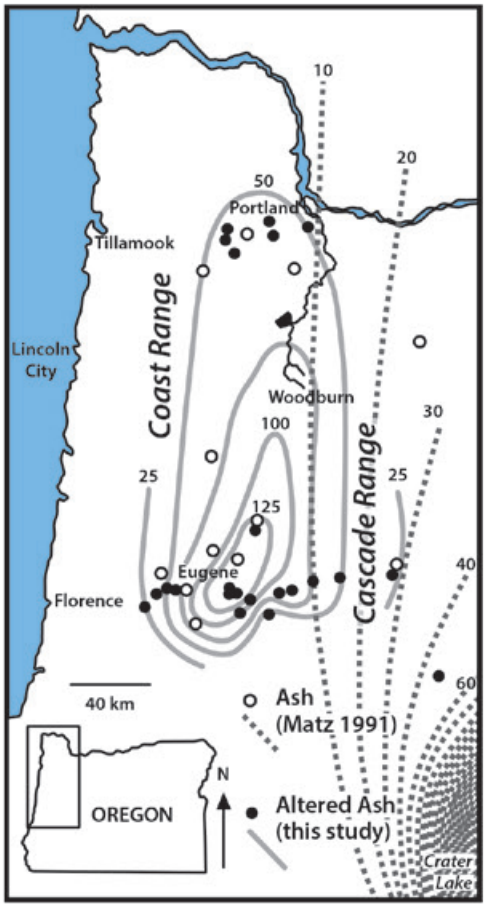

Figure 1. Isopachs (cm) of Malpass clay in the Willamette Valley (solid lines, representing approximate thickness) (James and Baitis 2003) compared with isopachs of Mazama ash (broken lines) (Matz 1991). In addition, 0.35-0.47 in (0.9-1.2 cm) of Mazama ash have been found at three locations in deep sea cores of the Oregon continental slope (Goldfinger et al. 2003), and 0.39 in (1 cm) of Mazama ash has been found in Little Lake in the Oregon Coast Range (Worona and Whitlock 1995).

The caldera-forming eruption of Mount Mazama approximately 7,600 years ago created Crater Lake, which is about 85 miles (136 km) southeast of Eugene and the southern end of the Willamette Valley (Figure 1). Most ash from Mount Mazama was borne eastward by prevailing winds from the Cascades onto desert soils and playa lakes of eastern Oregon, southeastern Washington, and northwestern Nevada (Crandell and Mullineaux 1978; Kittleman 1973; Matz 1991; Mehringer et al. 1977; Sarna-Wojcicki et al. 1981). However, pumiceous Mazama ash also has been identified in lake deposits of western Oregon (Williams 1942; Kittleman 1973; O'Connor et al. 2001; Worona and Whitlock 1995) and in offshore marine cores (Goldfinger et al. 2003). Early studies of the volume of ash issued from Mount Mazama, calculated by Williams and Goles (1968), theorized that more magma erupted than had been mapped. The authors of these studies explained the discrepancy with subterranean withdrawal of magma. This tech note proposes that some of the missing tephra was deposited into the Willamette Valley and weathered into Malpass clay and the Greenback Member of the Willamette Formation.

An airfall ash deposit into the Willamette Valley would have required a wind from the south or southeast, sending the ash north and west. Mazama ash is 0.35-0.47 in (0.9-1.2 cm) thick in submarine canyons of offshore Oregon (Goldfinger et al. 2003); 0.39 in (1 cm) thick in Little Lake in the Oregon Coast Range (Worona and Whitlock 1995);

and 3.9 in (10 cm) or more thick west of the eastern Willamette Valley (Matz 1991). Malpass clay fills in the intervening country, where fresh Mazama ash has not been found. Malpass clay in the Willamette Valley is an order of magnitude thicker than the predicted 0.4-4 in (1-10 cm) between the Cascades and Coast Range and was likely redeposited by wind and water into local depressions.

On May 18, 1980, the volcanic eruption of Mount St. Helens south of Seattle, Washington, showed similar ash distribution in the Pacific Northwest. The eruption began with a collapsing bulge of the volcano and a mudflow. Then a pyroclastic blast of mountain debris and hot volcanic gases shot out from the displaced bulge. Finally, a large Plinian column of gray ash shot 11 miles (18 km) into the atmosphere. Five subsequent vertical eruptions trailed off to the east at high elevation. Much of the column collapsed back on the volcano, distributing ash radially around the mountain; the ash redistributed later by landslides and rivers (Lipman and Mullineaux 1981). On May 25, 1980, winds sent airborne ash north and west to the coastal Washington towns of Grays Harbor, Oakville, and Hoquiam. Oakville received 0.75 in (1.9 cm) (Kliem et al. 2005). During this timeframe, Bureau of Land Management (BLM) (retired) soil scientist Karin Baitis observed 0.25-0.5 in (0.64-1.27 cm) of very fine, gray-colored ash at Hoquiam.

Geologic Setting of Malpass Clay and Dayton Soil

Stiff, gray and olive brown clays overlying Holocene alluvial deposits, paleosols, and Missoula flood silts in western Oregon's Willamette Valley have been called Dayton soils or the Malpass Member of the Willamette Formation (O'Connor et al. 2001). Malpass clay is associated with the Senecal and Calapooyia geomorphic surface, suggesting a Missoula flood provenance, according to Parsons and Balster (1967) and Parsons et al. (1970). The Dayton soil has been identified as a Mollisol (Haploxeroll) by Patching (1987), with a dark crumb-structured surface (A) horizon. Its subsurface gray clay has been considered the argillic (IIB2t) horizon of a Planosol by Parsons and Balster (1967) or an Alfisol (Albaqualf) by Patching (1987). Analyses by the authors of this tech note suggest that both the surface soil (Dayton series) and paleosol (Malpass clay) with abundant noncrystalline colloids and a rhyodacitic suite of sand-size minerals is better classified as an Andisol or, more specifically, a vertic Epiaquand (Soil Survey Staff 1998).

The West Eugene Wetlands in the southern Willamette Valley rest above impervious gray Malpass clay, which is 59 in (150 cm) thick, with a clay-size fraction between 65% and 75% and a medium sand fraction between 3% and 7%. In the northern Willamette Valley in Woodburn along Mill Creek (Figure 2), the gray clay varies in thickness from 20 to 47 in (51 to 120 cm), with a clay-size fraction between 80% and 85% and a medium sand fraction of barely 1%. In both places, the slickensided clay is separated by a clear erosional truncation from overlying silty soils and sediments. Well-drained slopes show an orange to yellow silty unit with characteristic rhyodacitic minerals, such as bipyramidal quartz, rather than gray clay. This rhyodacitic silt thins to 3.9 in (10 cm) at Blue River east of Eugene and to 2.4 in (6 cm) at Walton west of Eugene. The rhyodacitic silt thins to 3.9 in (10 cm) along the Middle Clackamas River east of Woodburn and to 3.9 in (10 cm) west of Forest Grove. The rhyodacitic silts on hillslopes are also known as the Greenback Member of the Willamette

Formation, and they extend well beyond the limits of Dayton soils and Missoula flood deposits (Parsons and Balster 1967). Well-drained Hazelair and Bellpine soils also include rhyodacitic minerals of Mazama ash, and they merge into Malpass clay on the valley floor. These other soils have only a dusting of rhyodacitic minerals and a bulk composition that reflects very different parent materials of bedrock hills. The Eocene-Oligocene Eugene and Fisher Formations (32-46 million years ago - Ma) to the south and east of Eugene are andesitic sandstones and conglomerates, with a few rhyodacitic ash-flow tuffs. The Oligocene-Miocene Little Butte Volcanic Formation (17-35 Ma) to the east of Eugene are rhyolitic and andesitic flows of a precursor of Cascadean arc volcanism. The Eocene Lorane Siltstone and Spencer Formation (41-46 Ma) and Tyee Formation (46-51 Ma) of the Coast Range to the west of Eugene are arkosic and micaceous from granitic source terranes (Retallack et al. 2004; McClaughry et al. 2010).

Figure 2. Mill Creek site in Woodburn, Oregon, where gray clay (stratum 2) lies between 1.5 ft (0.46 m) of alluvium on the surface and 3.8 ft (1.2 m) of organic peat below the surface. Radiocarbon dating of the gray clay (6,850 years before present) correlates directly to the Mount Mazama eruption (Stenger 2002).

A series of strata from different geologic events lie underneath the Willamette Valley floor. Malpass clay overlies the alluvial Willamette Formation deposits and grades into the Greenback Member extending laterally onto hillslopes both east into the Cascade Range and west into the Coast Range (Figure 3). The Malpass clay is thickest in the southern Willamette Valley and thins to the north (James and Baitis 2003). This contrasts with the Missoula flood silts that are thickest in the northern Willamette Valley and fine to the south (O'Connor et al. 2001). Previous researchers have considered the provenance of the Malpass clay as derived from the Willamette River system (McDowell 1991) based on descriptions of Willamette Formation characteristics (Balster and Parsons 1968; Glenn 1965). In their study, the Irish Bend silts were found at approximately 370 ft (113 m) mean sea level (msl), at which point the Malpass clay thickens and is located in low lying, poorly drained areas. The clay is variable in thickness, with the deepest deposits found in what appear to be relict cut and fill stratigraphic units. In West Eugene beneath the Malpass clay, as many as three paleosols (fluvents) were found. The soil profiles are thin and red and appear well drained. The Wyatt Member is found primarily in the northern part of the valley (Parsons et al. 1973). In the Springfield-Eugene area, an

alluvial fan consisting of Linn gravels underlies the entire area. In West Eugene, the gravels are within 12 ft (3.7 m) of the soil surface, sometimes outcropping in sideslopes or ditchlines along channelized Amazon Creek.

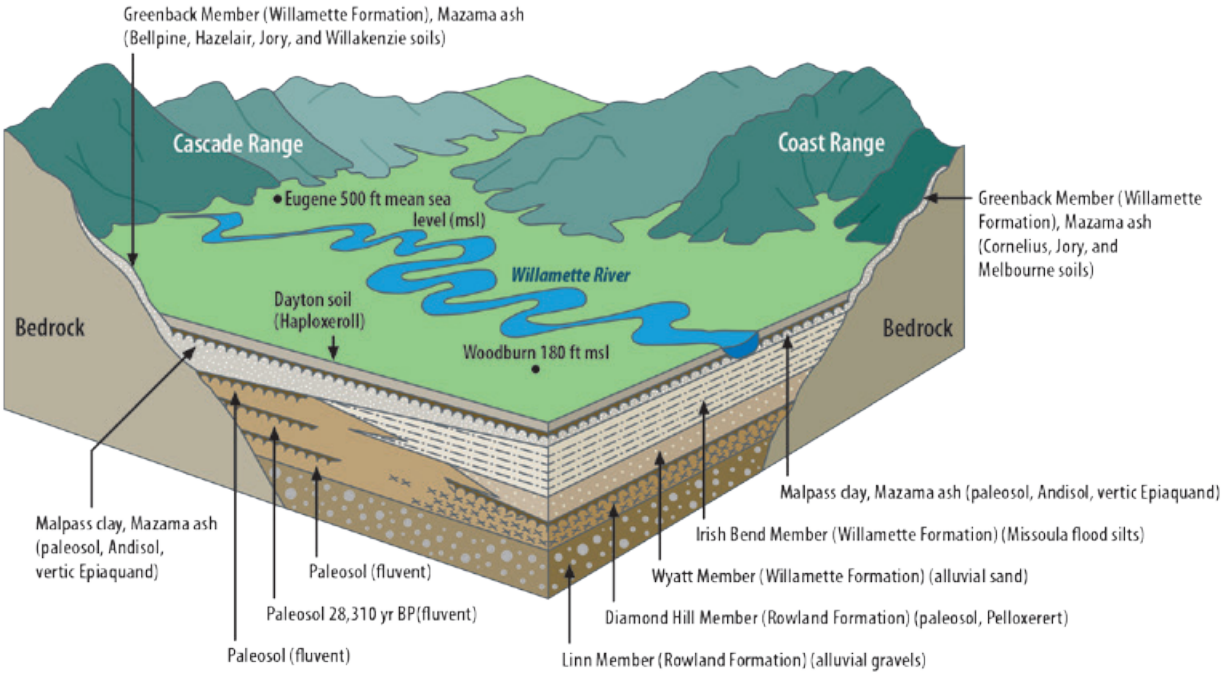

Figure 3. Exaggerated (not to scale) block diagram of the Willamette Valley between Eugene and Woodburn, with the stratigraphic framework developed by Balster and Parsons (1968, 1969) and with the superposition and extent of the Malpass clay and Greenback Member (thickest in Eugene and fining toward Woodburn) developed from this study.

Materials and Methods

Hand-auger holes were located across the Willamette Valley by using Natural Resources Conservation Service soil maps. Two trenches were excavated to a depth of 10 ft (3 m) in West Eugene, and 50 auger holes ranging between 2.5 to 10 ft (0.76 to 3 m) in depth were aligned in two east-west transects from the Cascade foothills to the crest of the Coast Range and one north-south transect from Cottage Grove to Portland. Soil and mineral data were collected from each soil boring at intervals of 4-6 in (10-15 cm). More than 150 samples were described and analyzed for minerals. Soil and rock were described using standardized soil taxonomy and geologic descriptions. In addition, random cores were analyzed in the West Eugene Wetlands throughout a 10-year period, and samples were collected for further lab analysis.

Samples were sieved with size 50 mesh (0.297 mm openings), and both coarser and finer fractions were studied under binocular and petrographic microscopes for mineral composition and character. Crystals were easily segregated by water and handpicked. Hornblende crystals were selected from nine samples from the Eugene and Woodburn areas as representative of likely modified Mazama ash from the valley floor (Malpass clay) and adjacent hillslopes (Greenback Member).

X-ray diffraction (XRD) analyses were submitted to two different labs at the University of Oregon: a Bruker instrument was used in the Center for Advanced Materials Characterization in Oregon (CAMCOR), and a Rigaku instrument was used in the Department of Geological Sciences. In addition, XRD was performed by J.R. Glasmann with the Willamette Geological Service using chemical treatments (James and Baitis 2003). Twelve polished thin sections were prepared in the University of Oregon thin section lab, with multiple grains of each mineral selected from representative sites. The thin section lab used a Cameca SX-50 electron microprobe at CAMCOR with four wavelength spectrometers with analytical conditions of 15 kiloelectron volts (keV) and 20 nanoamperes (nA). Standards are generally pure metals, oxides, and some silicates and glasses. CAMCOR used an FEI Qanta scanning electron microscope to obtain images characterizing distinctive minerals and volcanic grains. CAMCOR also used the Titan 80-300 instrument for transmission electron microscopy. Samples were prepared by diluting 100-150 g of each soil in 400 ml of distilled water. After agitation, the finest material in suspension after 2 or more days was extracted with a dropper. Each liquid sample was applied to a sample holder of copper wire mesh covered by a 5-nanometer (nm) layer of carbon. A single drop was placed with a sterile pipette on the holder, and slowly the liquid was dried off with the edge of adsorbent paper. The thin-layered sample was placed in the microscope under a vacuum where it was bombarded by high-speed electrons guided by strong electromagnetic rings. A high-resolution image was used to identify a mineral target, and X-rays generated from that area were collected by the detector and reported as TIFF files.

Radiometric dating ($^{40}Ar/^{39}Ar$) analyses were performed on hornblende mineral separates (0.50-0.75 mm), in order to determine crystal apparent ages. Mineral separates were cleaned in an ultrasonic bath of dilute nitric acid (HNO_3). Irradiation at the Ohio State University Nuclear Reactor Lab included the IHLHb-1 standard. Crystals were spot heated with the Spectron 65W Nd:YAG continuous infrared 1,064-nm laser. Spot ablation was approximately 80 micrometers (µm), and analyses were replicated three times within the core of the crystal. Water and other condensable gases were trapped by an N_2 cold finger. Evacuation of the sample chamber resulted in Ar volumes typically $< 3 \times 10^{-16}$ moles mV^{-1} ^{40}Ar. Under continuous laser beam mode, each sample was incrementally heated from 450° C to fusion (Lo Bello et al. 1987). ^{40}Ar and ^{39}Ar were measured in the VG 3600 mass spectrometer with a typical 4.5-kilovolt (kV) acceleration potential and 400-milliamp (mA) trap current. Using the electron multiplier system, $^{40}Ar/^{39}Ar$ yields for atmospheric argon were approximately 310 ± 0.3%.

Radiocarbon analyses on soil carbon were performed commercially by β-scintillation counting via benzene synthesis. Three samples were collected from a trench in West Eugene at 15 in (38 cm), 42 in (107 cm), and 65 in (165 cm) and sent to Beta Analytic for analysis. Two samples were collected in the West Eugene Wetlands in a soil core.

Stratigraphic Position of the Gray Clay in the West Eugene Wetlands

The inception of this study began with an assessment of soils on public lands managed by the BLM in the West Eugene Wetlands in 2001, using stratigraphic observations to identify depositional

units, particularly Missoula flood silts. No local archaeologic, engineering, or geologic reports were found documenting the presence of Missoula flood silts in the surrounding Eugene area; this study was designed to test whether they were present. Observations of trenches and cores taken during the course of this study concluded that the Missoula flood silts did not extend south of Eugene's Mahlon Sweet Field airport at an elevation of approximately 374 ft (114 m) msl. However, very massive amounts of gray clay were found in West Eugene, frequently overlain by thin veneers of Willamette River overbank flood deposits, which weathered into silty soils.

In West Eugene, the gray clay is always found in saturated conditions on the valley floor (Figure 4); it becomes impervious in winter, creating wetlands; it is gray and olive brown in color (2.5Y, according to standard soil color charts); and it varies in depth. The clay is massive with evidence of slickensides; possesses few clay skins; and has no soil particles, root channels, or bedding planes. It is found beneath an alluvial soil approximately 18 in (46 cm) thick. The clay has been found as thick as 5.8 ft (1.8 m). The clay-size fraction is typically between 65% and 75%, with a medium sand fraction between 3% and 7%, including a variety of rhyodacitic ash minerals (James and Baitis 2003, 2014).

Figure 4. The gray clay is massive, varies in depth, and is always found in saturated conditions on the Willamette Valley floor.

The gray clay is not found in well-drained hillslope positions. The same rhyodacitic suite of minerals is found on well-drained grayish red and brown soils of hillslopes (outside of saturated conditions), but without the gray clay (Figure 5). The silty surface soils on hillslopes (Greenback Member of the Willamette Formation) extend well beyond the limits of Dayton soils and Missoula flood deposits (Parsons and Balster 1967). Well-drained Bellpine, Cornelius, Jory, Hazelair, Melbourne, and Willakenzie soil series include some minerals of Mazama ash in the soils' upper inches (centimeters), which merges into the Malpass clay on the valley floor. The deposits are thickest in the southern Willamette Valley, thinning northward (James and Baitis 2003). The stratigraphic profile in Figure 5 displays the position of the gray clay from the hillslope to the valley floor. A paleosol was found at the base of each soil auger hole (James and Baitis 2003, 2014), directly beneath the gray clay. The paleosols are well-drained and red and brown, indicating that a well-oxygenated soil surface existed before the Mount Mazama eruption, back to about 28,000 years ago.

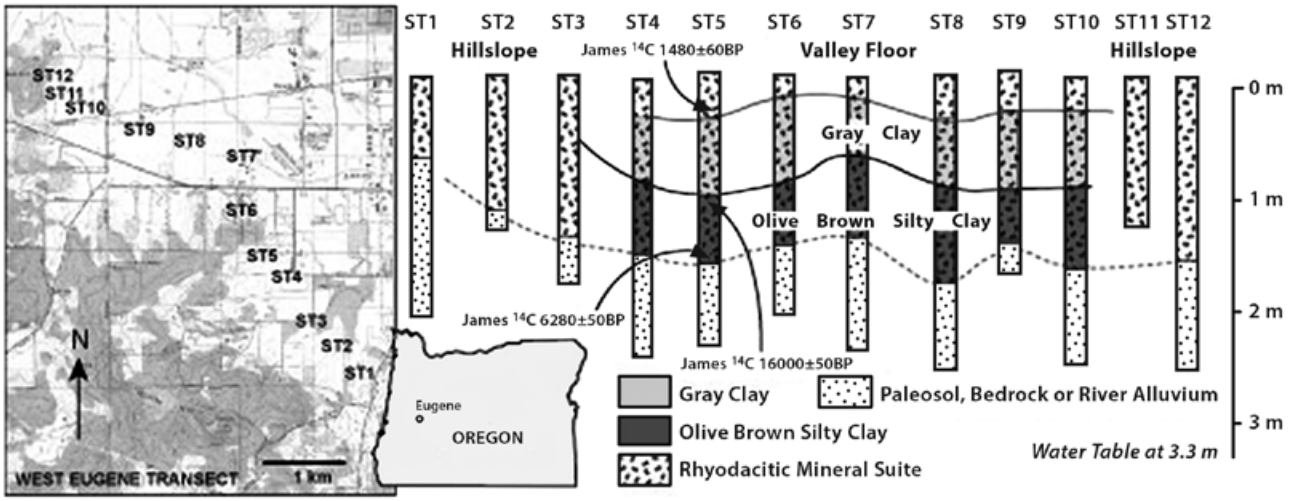

Figure 5. Transect locations of soil borings across the West Eugene Wetlands (to the left). The stratigraphic cores illustrate the gray clay found on the Willamette Valley floor under saturated conditions, while mineralogy reflects the ash found on the hillslope.

Table 1 provides an example of variation in soil textures from two sample sites (hillslope and valley bottom) in the West Eugene Wetlands. Rock fragment grains weather quickly in the moist valley floor sites and more slowly on well-drained hillslopes. Their demise results in the formation of gels and clays in the bottomland samples, which are evident in the 16.5% higher value in the fine texture category of sample BLM 9-4 (Table 1) (James and Baitis 2003). Sample BLM 9-4 has 10.8% less material in the "> 100 µm fine sand" category and 1.7% less material in the "> 50 µm coarse sand" category. In terms of visual inspection, the hillslope fraction is mainly volcanic glass and pumice, whereas the bottomland sample lacks both. Both samples include a unique suite of rhyodacitic minerals of sand size related to the Mazama eruption. The glassy tephra weathers easily to colloids in saturated valley bottom sites, yet it maintains a silty texture on better drained hillslopes.

Table 1. Textural comparison of hillslope reddish clayey silt (Sample BLM 12-3) and bottomland gray clay soils (Sample BLM 9-4), from James and Baitis (2003).

Sample #	Textural Class	Weight %	Sample #	Textural Class	Weight %
BLM 12-3	Clay 5 + 15 min	23.7	BLM 9-4	Clay 5 + 15 min	40.2
BLM 12-3	< 100 µm silt	51.6	BLM 9-4	< 100 µm silt	47.3
BLM 12-3	> 100 µm fine sand	19.7	BLM 9-4	> 100 µm fine sand	8.9
BLM 12-3	> 50 µm coarse sand	5.0	BLM 9-4	> 50 µm coarse sand	3.3

Chromatography

Anion content of groundwater and soil slurries was analyzed by chromatography at the University of Oregon (James and Baitis 2003) and by Apex Labs (James and Baitis 2014). High values of chloride and sulfate were found in the gray clay slurries at a sample site near Walmart in Willow Creek, but even higher values were found in nearby groundwater (from piezometers PZ-2i and PZ-4i) (Table 2).

Table 2. Chromatography results in parts per million from Apex Labs.

Sample Site	Date	Sample Number	Element	Result
Piezometer-4i	10/17/13	A3J0036-01	Chloride	1,130 ppm
		A3J0096-01RE1	Sulfate	8.17 ppm
Piezometer-2i	4/9/13	A12C521-01	Chloride	1,890 ppm
		A12C521-01	Sulfate	439 ppm
Willow Creek Walmart	11/7/12	A12J404-01	Chloride	64.7 ppm
		A12J404-01RE1	Sulfate	25.3 ppm
Willow Creek W Fork	2/25/13	A13Ba45-01	Chloride	4.42 ppm
		A13Ba45-01	Sulfate	161 ppm

High concentrations of chloride in the groundwater may be due to evaporation over the impermeable clayey substrate. The presence of volatiles indicates that these elements are weathering out of the Malpass clay. This points to a naturally high background level and is corroborated by regional conductivity studies. Elevated conductivities are consistently found throughout the Amazon Basin as compared to rivers in the Coast Range and Cascade Range (James and Baitis 2003).

Vertic Soil and Gilgai Relief

Gray clay on the Willamette Valley floor commonly shows gilgai microrelief (Figure 6, Photo A). The two kinds of gilgai relief in the West Eugene Wetlands include circular gilgai (vernal pools) and linear gilgai (microtopographic hummocks). Vernal pools are more than 35 ft (11 m) in circumference and less than 1 ft (0.3 m) in depth. Some of the cracks in the gray clay can reach in excess of 3 ft (0.9 m) in depth along Willow Creek (BLM Speedway parcel).

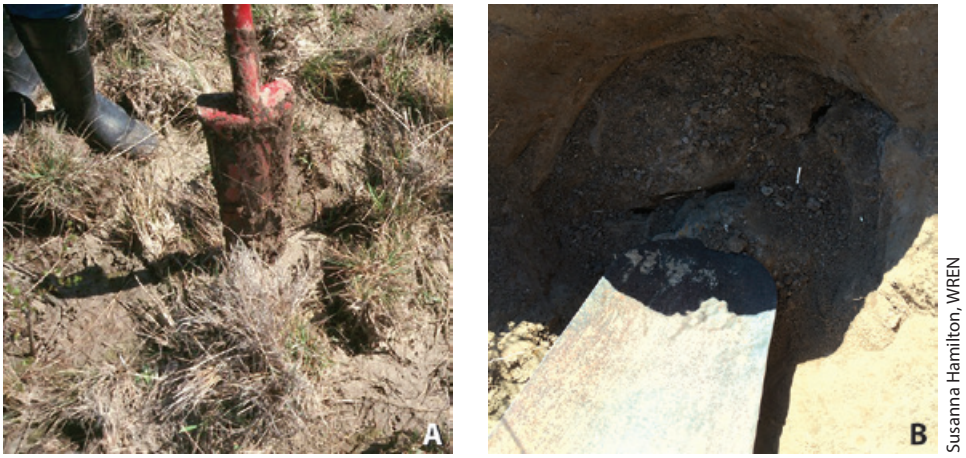

Figure 6. In photo A, the shrink/swell of the gray clay exhibits itself in linear gilgai relief in the form of hummocky microrelief. As part of the soil mass is forced upward to release pressure from compression, the formation of a mound occurs. Slickensides are a soil characteristic within the gray clay. The sides of the peds become shiny as they press against each other during the squeezing of the swelling clays. In photo B, taken on the BLM Balboa parcel, the Dayton IIBt begins approximately 12 in (30 cm) below the soil surface. Cracks become clearly evident in the gray clay hidden beneath a surface soil.

Soils are classified from the top down, using diagnostics of the surface horizon. However, the properties of the subsurface horizons may be used when measurements fall within a buried genetic horizon (Figure 6, Photo B). The IIB2t of the Dayton soil series (typically mapped where the gray clay is found) is approximately 16 in (41 cm) from the soil surface and typed as a fine, montmorillonitic, mesic Typic Albaqualf (Patching 1987). Taxonomically, based on the soil surface, the soil is classified as an Alfisol. The Dayton soil series are alluvial, and a lithologic discontinuity occurs at the B horizon (IIBt). It is here that the gray clay beneath the surface soil has vertic characteristics.

The formation of gilgai microtopography occurs from the shrinking and swelling of smectite clays that form deep cracks when dry (Kishne et al. 2009; Kodikara et al. 1999; Dinka and Lascano 2012). With rain, the clay swells and heaves the underlying material upward in polygonal patterns because the soil expands as its volume increases with moisture. In addition, surficial material that falls into the cracks during the dry season forces the soil mass upwards, which forms mounds. Small mounds and hollows grow in amplitude as the landscape buckles, creating microtopographic hummocks and intervening swales, which during the rainy season create vernal pools on the impermeable wet clays below. In Australia, circular gilgai are found on level ground and linear gilgai on modest slopes (Paton 1974), and this is true for Eugene as well.

X-Ray Diffraction

The University of Oregon's CAMCOR lab performed clay mineralogy studies using XRD on untreated clay samples from both a bottomland site from the BLM Nielsen parcel and a hillslope site from the BLM Oak Hill parcel in West Eugene. After sieving, samples were left to settle for 15 minutes, and floating clay particles were extracted. The samples were heated to 120° C and 600° C. The Bruker instrument was used with no chemical treatments.

The valley floor sample from the BLM Nielsen parcel displayed a diffuse peak from 4° to 7°, indicating noncrystalline colloids with minor smectite clay (Figure 7). Mica, kaolinite, and halloysite, expected from surrounding soils, were not present, since there were no peaks at 9°, 12°, or 14.5° 2θ.

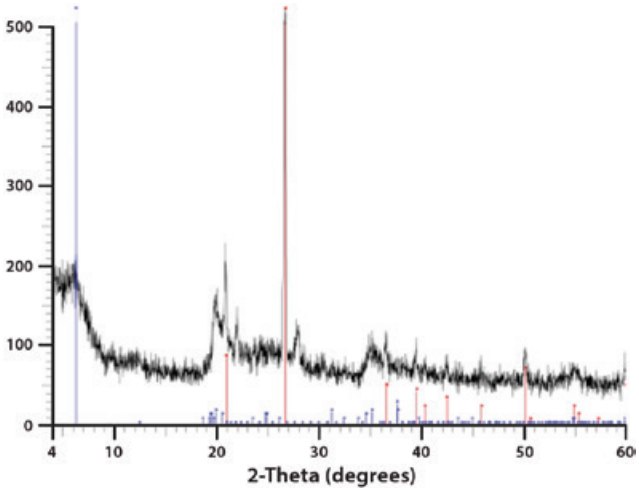

Figure 7. X-ray diffractogram of the gray clay sampled from the valley bottom in West Eugene at the BLM Nielsen parcel.

Quartz was indicated by peaks near 20.8°, 27°, 36.8°, 39.3°, 40.3°, 42.4°, 46°, 50°, and 55°2θ, and large bipyramidal grains were observed in this sample. Andesine plagioclase is also indicated by peaks at 5.2°, 19.5°, 25°, 35°, and 37.5°2θ.

A single pulverized pumice grain from the fine sand fraction of a hillslope soil also lacked clay peaks and was evidently volcanic glass, with small crystals of quartz and plagioclase (Figure 8).

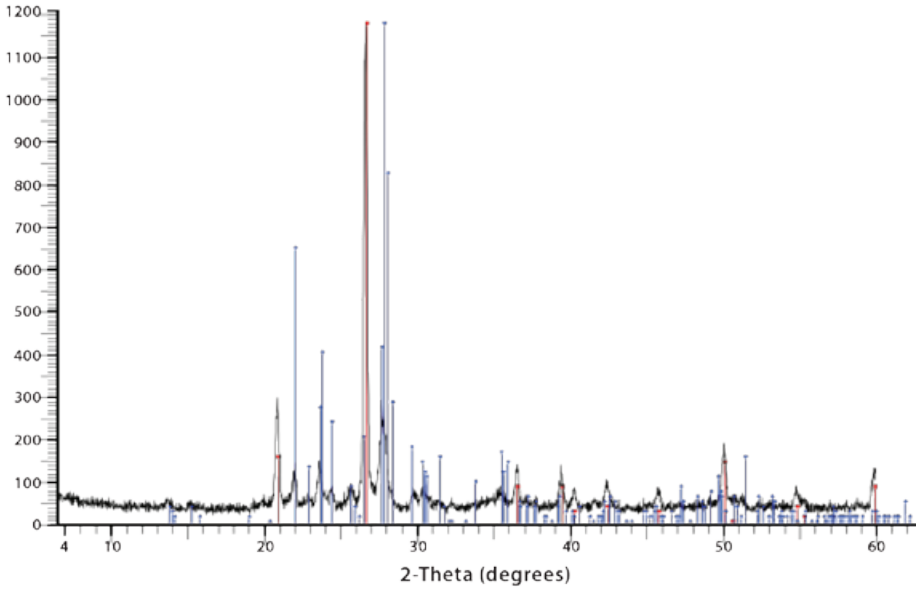

Figure 8. X-ray diffractogram of white lithic fine sand grains from a hillslope soil sample.

A third untreated XRD sample of the gray clay (Malpass clay), taken from a trench in the West Eugene Wetlands, was conducted in 2002 on the Rigaku instrument in the University of Oregon's Department of Geological Sciences. The results also supported a soil rich in amorphous material evolving slowly toward a 2:1 clay ratio.

XRD samples of the gray clay that were chemically treated by J.R. Glasmann (James and Baitis 2003) defined a smectite peak (Figure 9). Crystalline peaks were found to be quartz and plagioclase, similar to the untreated samples in Figures 7 and 8.

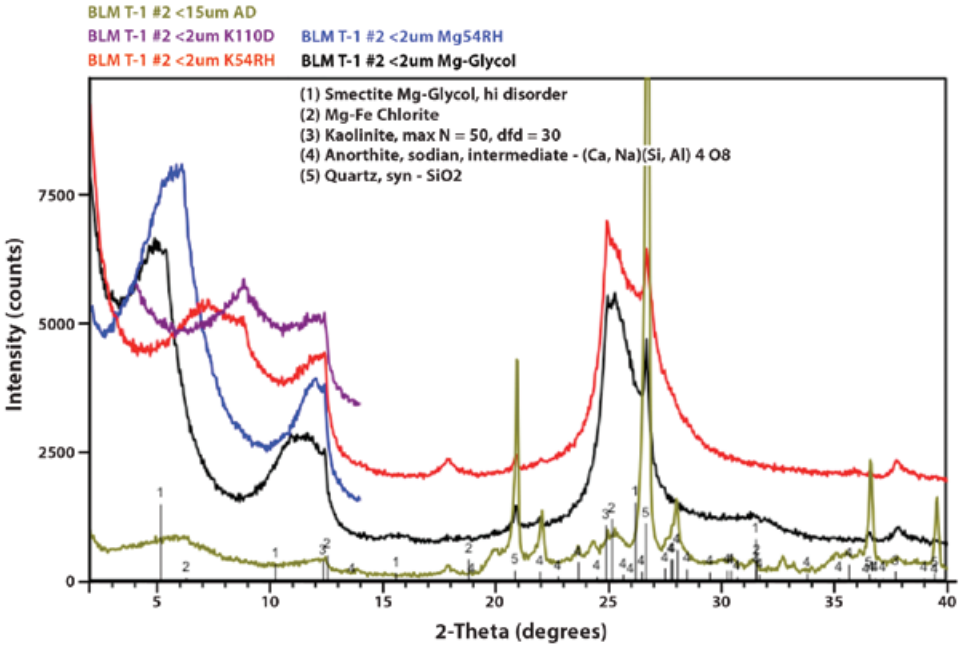

Figure 9. This x-ray diffraction pattern represents the silt and clay fraction of soil material from a sample found between 10 and 21 in (25 and 53 cm), using the glycol saturation method. The shifting peaks demonstrate that the clay is smectitic.

Volcanic glass and noncrystalline colloids are characteristic of Andisols (Soil Survey Staff 1998), in which devitrification of glass to amorphous weathering products, such as imogolite and allophane, is the primary weathering process. Andisols are generally young soils on fresh volcanic ash; with time, they gain clay, soil structure, and the features of other soil orders (Lowe 1986; Shoji et al. 1993). Such a model works well for the gray clay, which in the field has a sharp top like a discrete paleosol and has no clay skins and less structural development. Smectite clay is beginning to form and imparting gilgai structure even under a mollic surface and grassy cover.

Based on the analyses, the authors of this study recommend that the buried Malpass clay and its exposed Dayton soil series be reclassified as an Andisol and, more specifically, as a vertic Epiaquand (Soil Survey Staff 1998). The Andisol soil order was not available in the U.S. taxonomy at the time of previous soil surveys (Parsons and Balster 1967; Patching 1987), but judging from the high proportion of noncrystalline materials present in Malpass clay, this soil order is appropriate. Previously, Malpass clay was considered a buried soil, separated from the overlying Mollisol (Haploxeroll) (Patching 1987), or as a surface soil (Dayton series) (Balster and Parsons 1967). However, during this study, we found no genetic relationship between the surface soil and the Malpass clay, as implied by identification as a Planosol (Parsons and Balster 1967) or Albaqualf (Patching 1987). Also, there are no connecting clay skins or gradational contacts.

Transmission Electron Microscope EDX Analyses

Electron microprobe analyses confirm differences between the Malpass clay and the reddish gray silty hillslope soils. Samples of Malpass clay and underlying alluvium were collected from a valley bottom soil profile on the BLM Nielsen parcel to a depth of 8 ft (2.4 m). The sampling intervals were 1.8-2.7 ft (0.55-0.82 m), 3-3.7 ft (0.91-1.1 m), and 4.2-4.9 ft (1.3-1.5 m) within the gray clay. The sampling intervals were 6.2-7.0 ft (1.9-2.1 m) and 7.0-8.0 ft (2.1-2.4 m) from alluvial layers beneath the gray clay. Samples from weathered andesitic sandstones of the Eugene Formation were collected from a hillside located on the BLM Speedway parcel about 15-18 ft (4.6-5.5 m) above the valley floor and depths from the surface of 6 in (15 cm), 24 in (61 cm), 30 in (76 cm), and 36 in (91 cm). Weathered arkosic-micaceous samples of the Spencer Formation were collected from the BLM Greenhill parcel at depths of 5 in (13 cm), 16 in (41 cm), and 24 in (61 cm). Arkosic-micaceous samples of the Tyee Formation were collected from Panther Creek Road in upper Wolf Creek and also from IP Deeded Road west of Noti at a depth of 18 in (46 cm). Samples of basaltic andesites of the Little Butte Volcanic Formation were collected at Hills Creek east of Jasper from a depth of 12 in (30 cm) in a wetland and 12 in (30 cm) in a terrace.

The Malpass clay (Figure 10 and Table 3) can be contrasted with the underlying paleosols (Figure 11 and Table 4). Aluminum (Al) and silicon (Si) were common components of the gray clay, and frequently, silica alone was found. Rhyodacitic magmas are enriched in silica. The strong carbon (C) peak and small copper (Cu) peak was related to interaction between the electron beam and the sample platform. Few bases were represented in the paleosol, and no volatile elements were detected, compared with the Malpass clay. Chromatography analyses of the Malpass clay and Amazon Creek also indicated the presence of sulfur (S), chlorine (Cl), and fluorine (F). There is a direct relationship between the chemistry of the surface water and soil mineralogy in West Eugene.

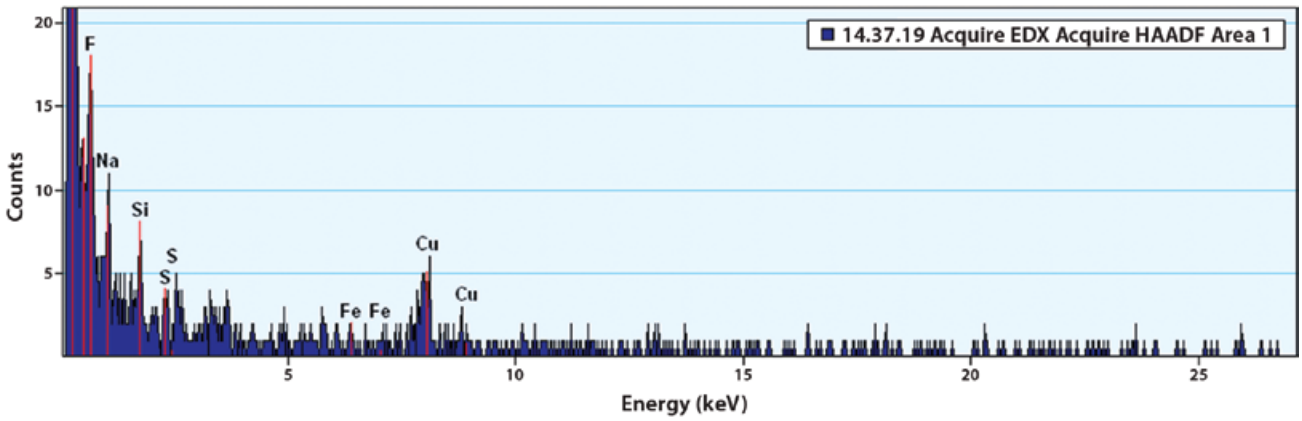

Figure 10. Spectral representation of gray clay collected from the BLM Nielsen parcel between 1.8 and 2.7 ft (0.55 and 0.82 m).

Table 3. Elemental composition of gray clay collected from the BLM Nielsen parcel between 1.8 and 2.7 ft (0.55 and 0.82 m).

Element	Weight %	Atomic %	Uncertainty %	Correction	k-Factor
Carbon (C)	98.95	99.57	1.44	0.26	4.032
Fluorine (F)	0.28	0.18	0.20	0.62	1.623
Sodium (Na)	0.11	0.05	0.03	0.81	1.181
Silicon (Si)	0.12	0.05	0.03	0.92	1.000
Sulfur (S)	0.07	0.02	0.02	0.93	1.015
Chlorine (Cl)	0.11	0.03	0.03	0.95	1.055
Iron (Fe)	0.00	0.00	100.00	0.99	1.359
Copper (Cu)	0.33	0.06	0.06	0.99	1.601

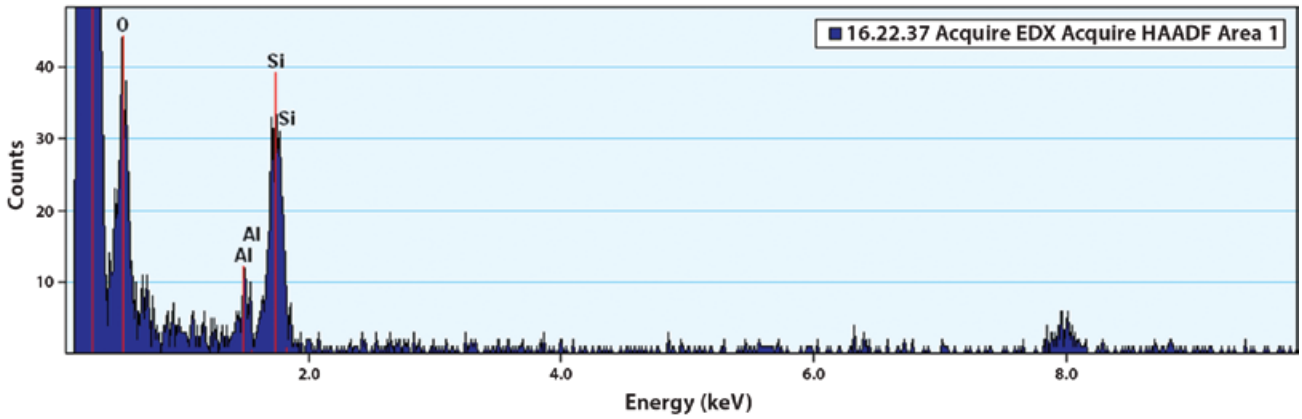

Figure 11. Spectral representation of a paleosol collected from the BLM Nielsen parcel between 7.0 and 8.0 ft (2.1 and 2.4 m).

Table 4. Elemental composition of a paleosol collected from the BLM Nielsen parcel between 7.0 and 8.0 ft (2.1 and 2.4 m).

Element	Weight %	Atomic %	Uncertainty %	Correction	k-Factor
Carbon (C)	93.79	95.98	1.46	0.26	4.032
Oxygen (O)	3.90	3.00	0.21	0.49	2.008
Aluminum (Al)	0.25	0.11	0.04	0.92	1.030
Silicon (Si)	2.04	0.89	0.10	0.92	1.000

Transmission Electron Microscope Images

The difference between an amorphous colloid of the Malpass clay and more crystalline bedrock was observed from examination at the nanometer scale in transmission electron microscope images (Figure 12). Samples of the gray clay appeared noncrystalline and wavy to dark without structure. In contrast, residual soil and bedrock appeared as brighter, thicker, angular crystalline materials. The glass of volcanic ash is itself amorphous and noncrystalline, and it weathers initially to noncrystalline colloids such as allophane or imogolite in Andisols (Lowe 1986; Shoji et al. 1983).

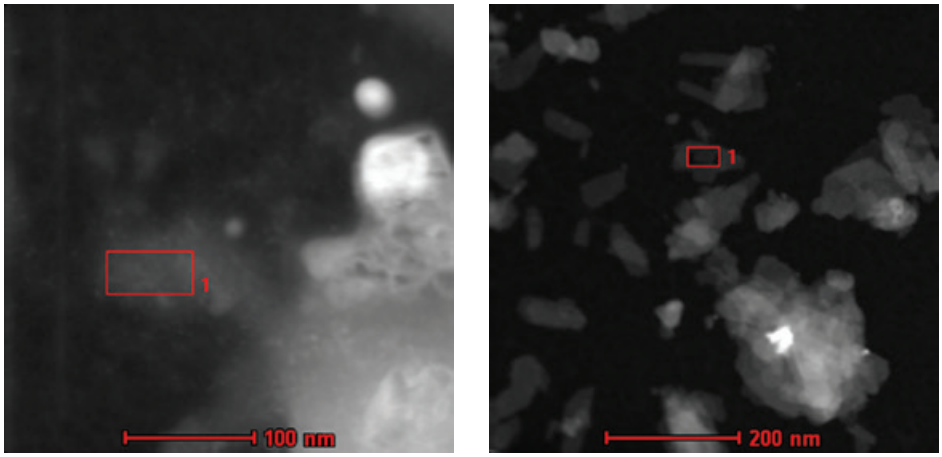

Figure 12. Transmission electron microscope images of gray clay. Noncrystalline gel (left). Bedrock crystalline structure (right).

Mineralogy of Gray Clay Unit

A distinctive suite of rhyodacitic minerals (Figure 13) was identified in the Malpass clay and Greenback Member of the Willamette Formation: (1) euhedral, tabular crystals of clear plagioclase (andesine-oligoclase); (2) euhedral, magnetic, light green orthopyroxene (hypersthene) with opaque inclusions of ilmenite and magnetite; (3) coarse-grained, dark brown to black hornblende; (4) coarse-grained quartz, both bipyramidal and singly pyramidal; (5) euhedral spinel; (6) flat hexagonal ilmenite with a dark green glass nucleus; (7) chromite; and (8) zircon. Other components included fine-grained granodioritic or rhyodacitic rock fragments and white to brown pumice and shards.

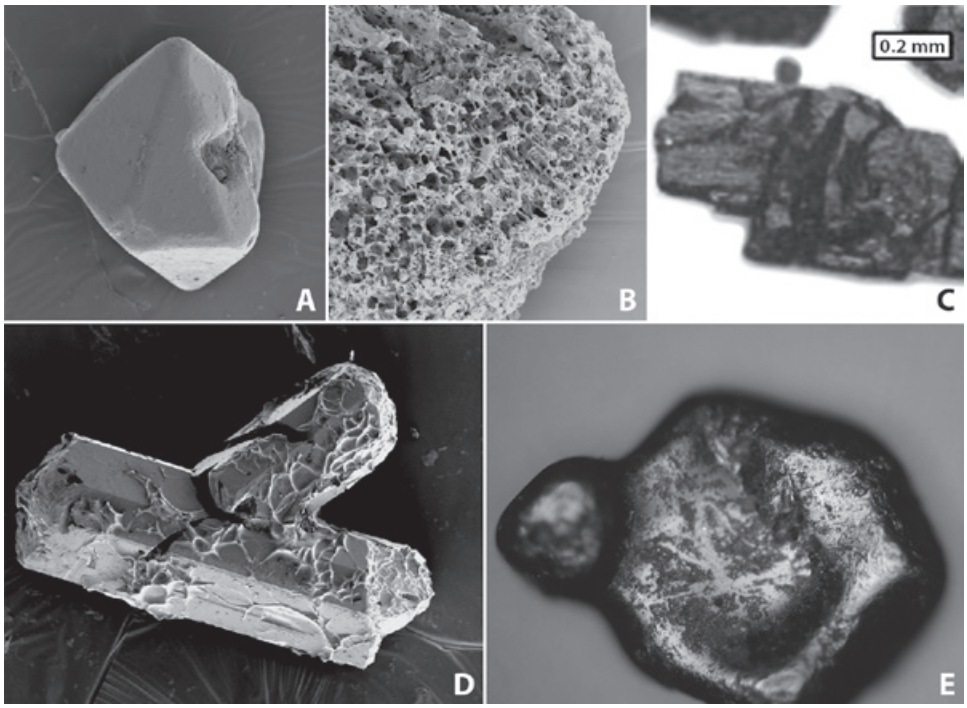

Figure 13. Volcanic minerals from gray clay collected in Eugene and Woodburn, Oregon: (A) bipyramidal quartz, (B) white to tan pumice with tiny tubules, (C) hornblende, (D) twinned hypersthene, and (E) hexagonal ilmenite. Note how well formed the minerals appear, with few signs of wear from fluvial transport.

Some of the mineral grains of the gray clay (Malpass clay and Dayton soils) are similar to those well documented in Mount Mazama ash (Kittleman 1973; Druitt and Bacon 1989; Bacon and Druitt 1988; Williams 1942). The dominant pyroxene mineral is hypersthene, which dominates clinopyroxene in Mazama ash (Kittleman 1973). Furthermore, the low-Calcium (Ca) (1.1% weight) pyroxene had abundant intergrowths of ilmenite and magnetite with nearly equal iron oxide (FeO) (19.7%) and magnesium oxide (MgO) (22.9%), which is very similar to Mazama hypersthene (Druitt and Bacon 1989). Hornblende grains were larger than the pyroxenes and nonmagnetic. Their total iron content was low (12%); their alumina content was high (10%); and their titania content was high (3.2%). Again, the match with Mazama ash is almost identical (Druitt and Bacon 1989).

In Eugene, a few glass shards were found floating freely in the clay matrix (Figure 14). The clay at Woodburn had more abundant glass shards and fine pumiceous material. Glass is readily weathered, and this may explain its rarity in the gray clay.

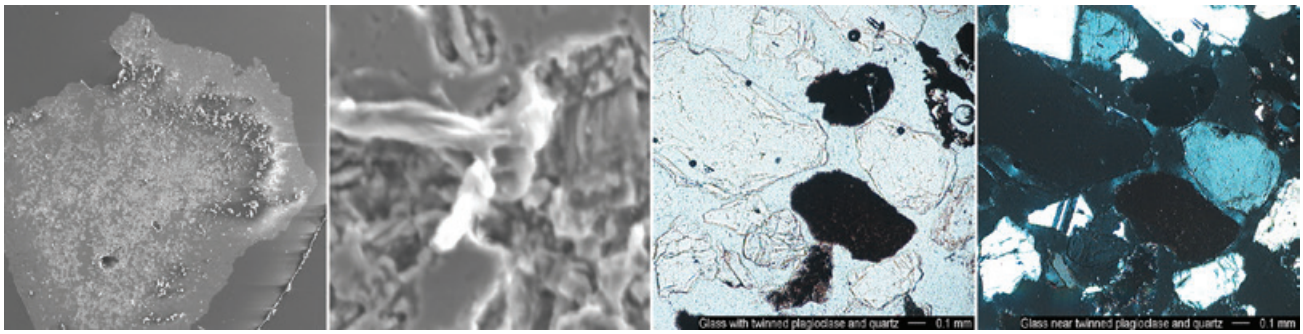

Figure 14. Glass shards found in clay samples collected in Eugene, shown under a scanning electron microscope and in thin section.

Other constituents common to the gray clay were not diagnostic of, but do not exclude, a Mazama ash source. Euhedral plagioclase grains showed zoning and twinning and a few with intergrowth of potassium feldspar (antiperthite). Plagioclase compositions were oligoclase-andesine (An30-36), with relatively equal calcium oxide:sodium oxide ($CaO:Na_2O$) values (6.7%:7.5%). Quartz was found in the gray clay but was not common in the rhyodacitic Mazama ash and was less common in other Cascade basaltic-andesite tephra. Lithic fragments with metallic inclusions appeared to have been hydrothermally altered and were of uncertain origin; ilmenite is common as a shiny black hexagonal platy mineral, sometimes with an angular depression or glass-filled core. Other accessory minerals included magnetite, titaniferous magnetite, ulvospinel, chromite, and hafnium-rich zircon.

Radiometric Ages

Radiocarbon

In Eugene, radiocarbon dates via scintillation counting were obtained from bulk soil carbon. The radiocarbon dates included 1,480 ± 60 yr before present (BP) at 7.9 in (20 cm) below the surface horizon of modern Mollisol; 16,000 ± 50 yr BP from the middle of the Malpass clay; and 6,280 ± 50 yr BP from the base of the Malpass clay. In addition, a date near the surface, but within the Malpass clay, was 2,930 ± 30 yr BP. In Woodburn, Oregon, Stenger (2002) reported a radiocarbon date of 6,850 ± 70 yr BP from charcoal in the Malpass clay.

Below the Malpass clay, a paleosol at 7 ft (2.1 m) was dated 28,810 ± 180 yr BP, which falls within the Wisconsin Glacial Stage. The sample had many carbon fragments. In a regional review, O´Connor et al. (2001) commented that the age of surfaces beneath the Missoula flood silt deposits, throughout the valley, ranges between 22,000 and 28,000 years ago, but no Missoula flood silts have yet been found in West Eugene.

Radiocarbon dating of the Malpass clay is thus comparable with that of the climactic Mount Mazama eruption of 6,845 ± 50 radiocarbon yr (Bacon and Druitt 1988), calibrated to 7,627 ± 150 yr BP (Zdanowicz et al. 1999). The anomalous 16 kiloannus (ka) ^{14}C date in Eugene may represent fossil plant material carried in the climactic eruption of Mount Mazama, while a younger 2,930 ^{14}C date can be explained by a high water table, plant rooting, or debris falling down soils cracks.

Argon/Argon ($^{40}Ar/^{39}Ar$)

Hornblende crystals from the Malpass clay and Greenback Members collected in West Eugene and Woodburn yielded apparent ages of 7,987 ± 102, 8,451 ± 57, and 8,540 ± 48 yr BP. Laser probe step-heating plateau ages (Figure 15) represented weighted means of the ^{39}Ar release spectra. The stepwise Ar release patterns were well developed and consistent among the three samples with 2σ less than 102 yr. These hornblende crystals did not exhibit recognizable excess ^{40}Ar.

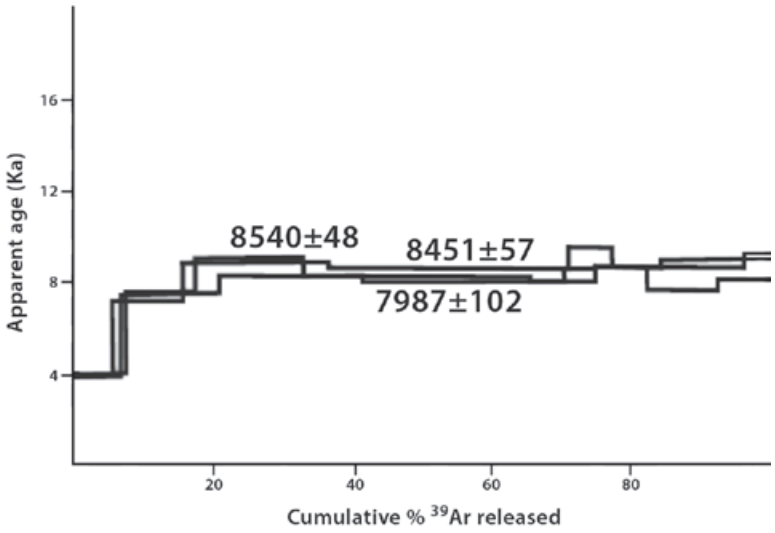

Figure 15. $^{40}Ar/^{39}Ar$ laser fusion dating yielded apparent ages of 7,987 ± 102, 8,451 ± 57, and 8,540 ± 48 yr BP.

Mount Mazama erupted about 7,600 years ago, according to radiocarbon dating (Zdanowicz et al. 1999). Given known variation in magmatic crystal ages (Simon et al. 2008), the $^{40}Ar/^{39}Ar$ dates presented here are compatible with origin from Mount Mazama.

Palynology

Mantling of the Willamette Valley with a 0.39- to 3.9-inch (1- to 10-cm) layer of fine textured volcanic ash from Mount Mazama would have changed the species composition of vegetation in the Willamette Valley, particularly where airfall ash fell and then washed into swales with depth. Paleoecologic data (pollen studies) from Beaver Lake near Corvallis, Oregon, in the mid-Willamette Valley (Pearl 1999) indicate that the Willamette Valley experienced a pronounced change in drainage after 7,500 calibrated yr BP, coincident with the Mount Mazama eruption (Figure 16). Xeric species, such as oak, fir, and alder, adjacent to riparian gallery forests (Pearl 1999) were suddenly replaced with grass, Oregon ash, willow, and other wetland-tolerant plants. These data demonstrate that after the Mazama ash fell, wetlands were created throughout the Willamette Valley.

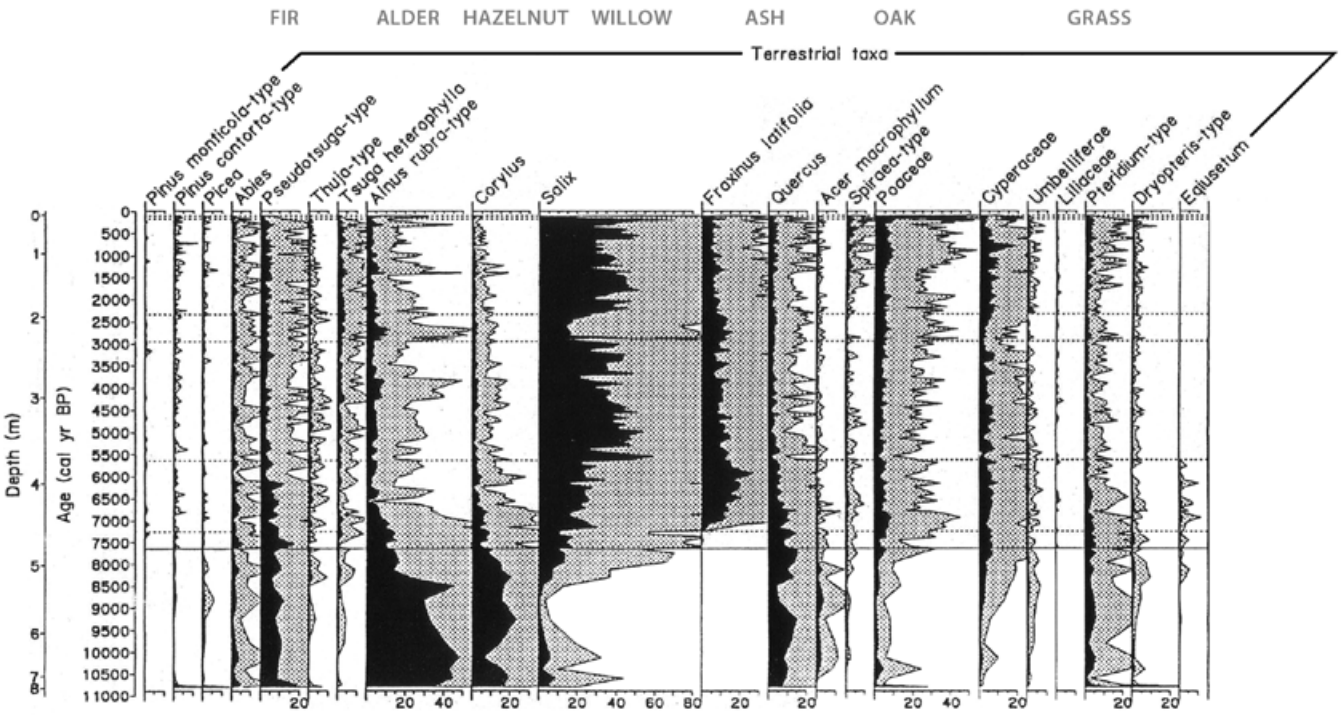

Figure 16. Display of how the vegetative species composition around Beaver Lake in the central Willamette Valley shifted dramatically to wetland species after the Mount Mazama eruption some 7,600 years ago (Pearl 1999).

Conclusions

This study contradicts previously held ideas that Malpass clay and the Greenback Member of the Willamette Formation are of an alluvial or lacustrine origin or related to flooding of the Willamette Valley by the Missoula floods. Instead, Malpass clay and the Greenback Member are considered weathered remnants of volcanic ash from the eruption of Mount Mazama some 7,600 years ago.

Paleoecologic data from Beaver Lake in the mid-Willamette Valley indicate that the Willamette Valley experienced a pronounced change in drainage after Mount Mazama erupted (Pearl 1999). Suddenly, wetland habitats appear, replacing more xeric species, such as oak, fir, and alder, adjacent to riparian gallery forests.

A unique suite of minerals related to Mount Mazama are found in the gray clay: (1) euhedral, tabular crystals of clear plagioclase (andesine-oligoclase); (2) euhedral, magnetic, light green orthopyroxene (hypersthene) with opaque inclusions of ilmenite and magnetite; (3) coarse-grained, dark brown to black hornblende; (4) coarse-grained quartz, both bipyramidal and singly pyramidal; (5) euhedral spinel; (6) flat hexagonal ilmenite; (7) chromite; and (8) zircon.

Hornblende crystals analyzed by $^{40}Ar/^{39}Ar$ dating yielded apparent ages of 7,987 ± 102, 8,451 ± 57, and 8,540 ± 48 yr BP. These dates fall within the bounds of the Mount Mazama eruption, given known variation in magmatic crystal ages (Simon et al. 2008). These dates also fall within the bounds of Mazama ash with a radiocarbon date of 6,850 ± 70 yr BP from Woodburn (Stenger 2002). Below the gray clay of the West Eugene Wetlands, the paleosols are well drained and date back to

28,810 yr BP. No Missoula silts, which are 12,500 years old, were found in the West Eugene area.

The two types of gilgai relief in the West Eugene Wetlands include circular gilgai (vernal pools) and linear gilgai (microtopographic hummocks). These features were created by the shrink/swell and vertic properties, which are characteristic of the gray clay unit found throughout the wetlands (Paton 1974). The gray clay has a weak signature of disordered smectite clay (montmorillonite); has characteristics of a colloid with little crystallinity; and has a chemical relationship of silica to aluminium represented as 2:1 or 3:1. The clay has little to no soil structure and no clay skin development.

This mineralogically distinctive soil layer derived from the climactic 7,600-year-old Mazama eruption serves as a geochronological time marker in the Willamette Valley, presented by surface soils of the Dayton series and a buried soil of the Malpass clay. Although these have been regarded in the past as Alfisols and Mollisols (Parsons and Balster 1967; Patching 1987), the demonstration of noncrystalline colloids indicates that the Dayton soil series and Malpass clay are better classified as Andisols and, more specifically, as vertic Epiaquands (Soil Survey Staff 1998). The Malpass clay represents a paleosol developed between about 4,000 and 7,000 years ago, before cover by silts and Mollisols. Both the Malpass clay paleosol and the surface Dayton soil series have been arrested in their development by poor drainage in lowland locations and exacerbated by their fine grain size. Other soils of the Willamette Valley were rejuvenated by Mazama ash fall but lost most of their volcanic glass and imogolite to retain only a dusting of rhyodacitic minerals of the Greenback Member. These Hazelair and Bellpine soil series are Haploxerolls and Halpoxerults (respectively), which have progressed beyond the Andisol stage of weathering.

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